TENNESSEE VALLEY AUTHORITY
RESOURCE GROUP, ENGINEERING SERVICES
HYDRAULIC ENGINEERING

ANALYSIS OF THE PARADISE FOSSIL PLANT COOLING SYSTEM:

THE IMPACT ON GENERATION OF ADDITIONAL COOLING TOWERS

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EXECUTIVE SUMMARY

An analysis was performed to quantify the impact of cooling tower capacity on generation at the Paradise Fossil Plant. Specifically addressed is the addition of cooling towers and/or upgrading the existing towers. Not addressed is the construction cost of such enhancements. The analysis includes a parametric study to quantify the impact of the cooling tower performance and condenser cleanliness. For the purposes of this analysis the plant availability was assumed to be 100 percent. The cost of additional fuel to maintain full capacity (megawatts) was converted to an equivalent loss in capacity so that a single impact quantity could be computed. The impact is given in terms of generation (gigawatt-hours per year) and referenced to the base case (current estimated tower performance and design condenser cleanliness).

The steam turbo-generator performance was based on TVA heat balances and General Electric (GE) backpressure correction curves. The condenser performance was based on the Heat Exchange Institute (HEI) method. Fourteen years of intake temperature and river flow were used (1976-1989), as this is the most extensive interval of data available in electronic form. The same fourteen years of meteorology were obtained from the National Weather Service (NWS) at the Louisville, Kentucky Airport (SDF), as this is the closest location where dry-bulb and dew-point are measured and logged in electronic format. The environmental constraints used are those in the November 1992, NPDES permit (89°F maximum fully-mixed downstream and 10°F maximum fully-mixed rise).

It is shown that PAF is susceptible to variable meteorology and hydrology, condenser cleanliness, and cooling tower capability, in that full capacity is limited by these factors. The estimated current condenser cleanliness and cooling tower performance is near the condition where susceptibility is pronounced. While there is a diminishing return on condenser cleanliness and cooling tower capability, the current performance of PAF is still within the range of significant return. As maintenance is not possible while the units are operating, and the performance is most needed during hot weather conditions, reserve performance is needed to assure full capacity during these conditions.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ANALYSIS OF THE PARADISE FOSSIL PLANT COOLING SYSTEM: THE IMPACT ON GENERATION OF ADDITIONAL COOLING TOWERS

PURPOSE

The purpose of this analysis is to quantify the impact of the performance of the Paradise Fossil Plant (PAF) heat rejection system on the net capacity[1] and generation[2]. This analysis was performed for the PAF Technical Services Group, in order to assist them in making recommendations for potential modifications to the heat rejection system, specifically increasing cooling tower capacity.

ASSUMPTIONS

A number of assumptions were made in order to model the operation of PAF and its response to river conditions, meteorology, and NPDES discharge constraints. The results obtained are contingent on the assumptions described in the following sections.

Steam Turbo-Generator Performance

The steam turbo-generator performance was taken from TVA heat balances labeled 47K1110-XX-R1 (where "XX" represents a series of drawings), each based on 1.5 inches Hga backpressure. These heat balances cover approximately 25 percent to 105 percent rated capacity. All are computed based on condenser zone backpressures of 2 inches Hga. The backpressure correction curves are GE drawings and labeled accordingly. These data were used to compute the generator output and condenser heat rejection from heat input and backpressure. For Unit 3, the dual backpressures were accounted for, as well as the differing condenser heat rejections due to the cascading of the condensate.

Limiting Backpressure

The limiting backpressure can have a pronounced effect on the magnitude of the computed impact on generation and capacity. A limiting backpressure of 4.5 inches Hga was used in the present analyses. In the simulations, capacity was reduced, if necessary, such that this limit was not exceeded for any unit at any time.

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[1] Plant capacity refers to a rate of production (i.e., megawatts).

[2] Plant generation refers to an accumulation of production over time (i.e., megawatt-hours).

Condenser Performance Calculations

The performance of the condenser was computed based on the currently recommended HEI Standards for Steam Surface Condensers [HEI, 1989]. Condenser configuration was taken from Technical Note 55, Volume 3 and Supplement 4.

Condenser Cleanliness

The design condenser cleanliness for PAF is 85 percent. A range of 50 to 95 percent was used in the present analysis. A cleanliness of 95 percent has been achieved after cleaning. Some recent calculations indicate that the cleanliness may drop significantly below 85 percent; thus a lower bound of 50 percent was selected.

Cooling Tower Performance

The performance of the cooling towers was computed based on the manufacturer's contract curves--subject to the following qualifications:

There has been some question in the past as to the performance of the towers, including how well they performed at the time of the acceptance test in 1969 ["Acceptance Test Report: Cooling Towers Paradise Steam Plant Units 1-3," TVA Division of Engineering Design Report No. 40-47]. There are also more than one set of performance curves associated with the PAF towers. As detailed in a memorandum of November 22, 1989 ["Paradise Fossil Plant Cooling Tower 2 Performance Technical Specifications," D. Benton, Engineering Laboratory to L. Brown, Fossil and Hydro Engineering], the Hamon performance curves and documents having the most recent dates do not agree with the December 18, 1965 contract with the constructor, Ragnar Benson Inc.

The 1969 acceptance test concluded that the towers provided 2.3°F to 3.4°F colder water than specified in the contract (indicating a capability or performance significantly above 100 percent). However, if the later Hamon curves [labeled H.1.51o1.N8.5-9], are used, the cold water temperature measured during the acceptance test is within a few tenths of a degree of the expected temperature (indicating a capability or performance of essentially 100 percent).

The original manufacturer's design calculations were performed by Marcel LeFevre when he worked for Hamon in Belgium. Mr. LeFevre's personal records indicate that the latter curves are applicable. Based on these latter curves, the PAF towers have never performed significantly above what Hamon (the subcontractor) thought was required. This is in direct contrast to what is indicated in the contract with Ragnar Benson (the principal contractor) and the 1969 acceptance test.

The performance of the towers, as indicated on the Hamon curves, was stated in the 1989 Tower 2 refurbishment contract Technical Specification (also with Hamon) [T.S. 79091A] and is summarized in Table 1. Tower 2 was renovated and upgraded to the performance listed in Table 2. This upgraded performance is approximately 15 percent greater than that corresponding to the original performance.

Table 1. Original Performance Criteria

	Spring/Fall	Summer
Water Flow [gal/min]	253,390	253,390
Inlet Water Temp [°F]	102.5	116.0
Exit Water Temp [°F]	75.0	87.5
Range [°F]	27.5	27.5
Dry-Bulb [°F]	57.3	77.9
Wet-Bulb [°F]	52.2	72.6

Table 2. Tower 2 Upgrade Performance Criteria

	Spring/Fall	Summer
Water Flow [gal/min]	253,390	253,390
Inlet Water Temp [°F]	100.0	112.5
Exit Water Temp [°F]	72.5	85.0
Range [°F]	27.5	27.5
Dry-Bulb [°F]	57.3	77.9
Wet-Bulb [°F]	52.2	72.6

The current performance of the PAF cooling towers can be estimated from a condenser heat balance. These calculations indicate that the performance of Towers 1 and

3 is at least 85 percent and possibly close to 100 percent of that indicated in Table 1, and that Tower 2 performs quite closely to that indicated in Table 2.

The simulations were performed over a span of tower performance. The base case was taken to be 85 percent (of Table 1) for Towers 1 and 2, and 100 percent (of Table 2) for Tower 2. As the upgraded performance (Table 2) is essentially 15 percent higher than the original, the base case can also be represented as 85/115/85 percent of the original performance for Towers 1/2/3, respectively.

The performance of cooling towers is typically expressed as percent capability. Capability is defined as the ratio of the actual water flow to the contract water flow, which should result in the same inlet and exit water temperatures for the same dry-bulb and wet-bulb temperatures. A tower which has a capability of 115 percent should be able to cool the contract water flow to some lower temperature, or 15 percent additional water flow to the same temperature stated in the contract. A tower with a capability of 85 percent should be able to cool the contract water flow to some higher temperature, or only 85 percent of the contract water flow to the same temperature.

Because tower performance as indicated by capability is computed as if the water flow were split evenly between several or fractional towers, this parameter lends itself directly to simulations considering upgrading existing towers or adding additional towers in parallel. As natural-draft towers rely on heat load to produce draft, these cannot be added in series. Mechanical-draft towers could be added in series; however, this would require additional fan and lift pump service as well as an intermediate water collection basin. Because of these considerations, parallel towers are thought to be the most feasible alternative. The combined capability of the towers in parallel (whether this corresponds to three physical towers or the three existing plus additional towers) is used for the performance index for the simulations.

Water Flowrate

The water flowrate was assumed to be directly proportional to the number of pumps operating. The design pump flows listed in Table 3 were used. There is some indication that the actual pump flows are less than the design. If this were the case, then the condenser rise would be higher as would be the tower range.

The variation of tower range and tower exit water temperature with tower water flow for a fixed heat input is shown in Figure 1. In this case, tower range was set equal to condenser rise and closed mode was assumed (i.e., tower exit water recirculated to condenser inlet).

The left and right axis scales are the same in Figure 1 (i.e., they both span 18°F). The difference between the minimum and maximum range (i.e., the solid line) is larger than the difference between the minimum and maximum tower exit water temperature (i.e., the

Table 3. Pump Flows

Pump	Number	Flow [gal/min]
Intake	6	82,300
Supplemental	4	124,500
Circulating	3	128,000

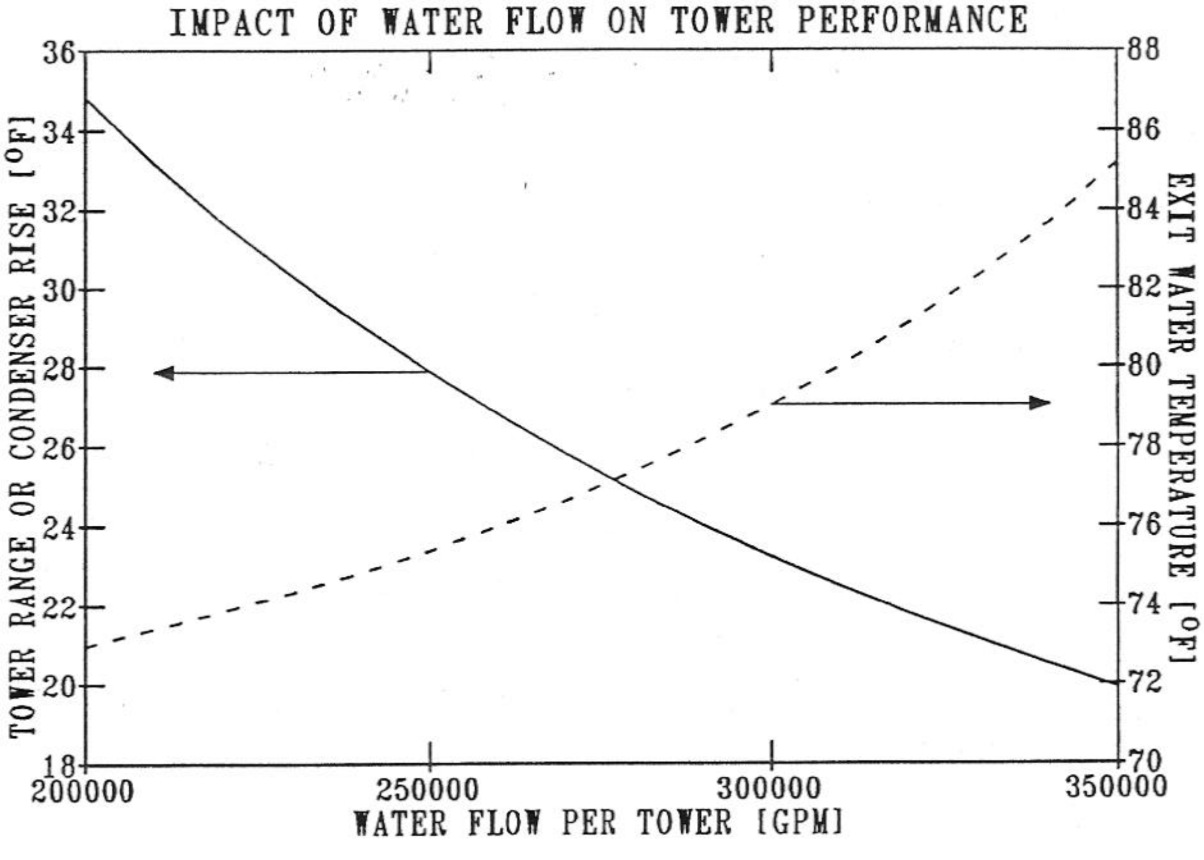


Figure 1. Impact of Water Flow on Tower Performance

dashed line). This shows that the tower exit water temperature and thus, condenser inlet water temperature, is less sensitive to variation in flow than is the condenser rise. As the water flow increases, the condenser rise decreases, and the tower exit water temperature increases. These two effects, being opposite in sign, are partially cancelling. This means that an uncertainty in pump flows will result in a smaller uncertainty in the overall analysis results. If the actual pump flows are less than design, then the computed losses in plant capacity and generation would be underestimates as would be the computed benefits of improved tower and condenser performance.

Operational Configuration and Cooling Mode

The operational configuration or cooling mode was selected on a step-by-step basis during the simulations such that the greatest net capacity resulted, subject to the operational and NPDES discharge constraints. All combinations of intake, supplemental, and circulating water pump operations were considered at each time step.

Intake Temperature

Fourteen years of intake temperature and river flow were used (1976-1989), as this is the most extensive interval of data available in electronic form.

Meteorology

The same fourteen years of meteorology were obtained from the National Weather Service (NWS) at the Louisville, Kentucky Airport (SDF), as this is the closest location where dry-bulb and dew-point are measured and logged in electronic format.

Environmental Constraints

The environmental constraints used are those in the November 1992, NPDES permit (89°F maximum fully-mixed downstream and 10°F maximum fully-mixed rise).

Service Load

The service load was taken to be a percentage of the generator output (based on the TVA heat balances as documented previously), plus the electrical requirement of the operating pumps (intake, supplemental, and circulating). The optimal selection of pumps was determined from the net capacity or the 3-unit generator output, less the unit service loads, less the pump service.

Quasi-Steady Analysis

Simulations were carried out using historical data. The response of the plant was assumed to be quasi-steady. That is, the transient response is modeled as a sequence of different steady-states. The difference between a quasi-steady and a true transient analysis is that the "short" time response is ignored. "Short" is a relative term and is used here as a comparative to the time increment for the analysis, which was one day. A daily time step was used as this frequency of the available river stage and intake temperature as well as the compliance period. This quasi-steady analysis presumes that the plant response will essentially track the environmental conditions on a daily basis.

Availability

The unit availability was assumed to be 100 percent. In actual experience, the availability is less, depending greatly on renovations at PAF. As guide values of availability are a policy determined by Generating Group management, adjusting the impact for availability is beyond the scope of this analysis.

RESULTS

The methodology and results of the analyses are based on the previously-stated assumptions and are as follows:

Impact of Condenser Cleanliness and Environmental Variability

Figure 2 shows the computed generation on a yearly basis relative to the base case of 85 percent condenser cleanliness and 85/115/85=285 percent total tower capability. The base case is indicated in Figure 2 as the intersection of the vertical dashed line at 85 percent condenser cleanliness, and the horizontal dashed line at 0 gigawatt-hours/year. The average impact is given by the solid line which begins at 50 percent condenser cleanliness and -227 gigawatt-hours per year and extends to 100 percent condenser cleanliness and +21 gigawatt-hours per year. The long dashed curves above and below the solid curve are the maximum and minimum, respectively, for the time interval covered in the simulation. The chain-link curves above and below the solid curve are the 95 percent confidence interval. Statistically, the 95 percent confidence interval indicates the variability which can be expected. Stated in another way, 95 years out of 100 should lie within the chain-link curves; and 5 years out of 100 should lie beyond.

Figure 2 shows that the variability present in the environment impacts generation by ±144 gigawatt-hours/year at a condenser cleanliness of 85 percent and the base case tower performance (i.e., the 95 percent confidence interval extends from -144 to +143 where the vertical dashed line for the base case intersects the curves). The impact of condenser cleanliness varying from 50 percent to 100 percent for the average year is 248 gigawatt-hours per year (i.e., the solid line begins at -227 and extends to +21). The magnitude of impact of these two variables is similar (i.e., 287 vs. 248). This means that the plant as it is configured is quite susceptible to changes in meteorology and hydrology. This is with the latest NPDES discharge permit limits. Previous analyses have shown that the susceptibility of the plant to previous, more restrictive discharge limits is substantially greater.

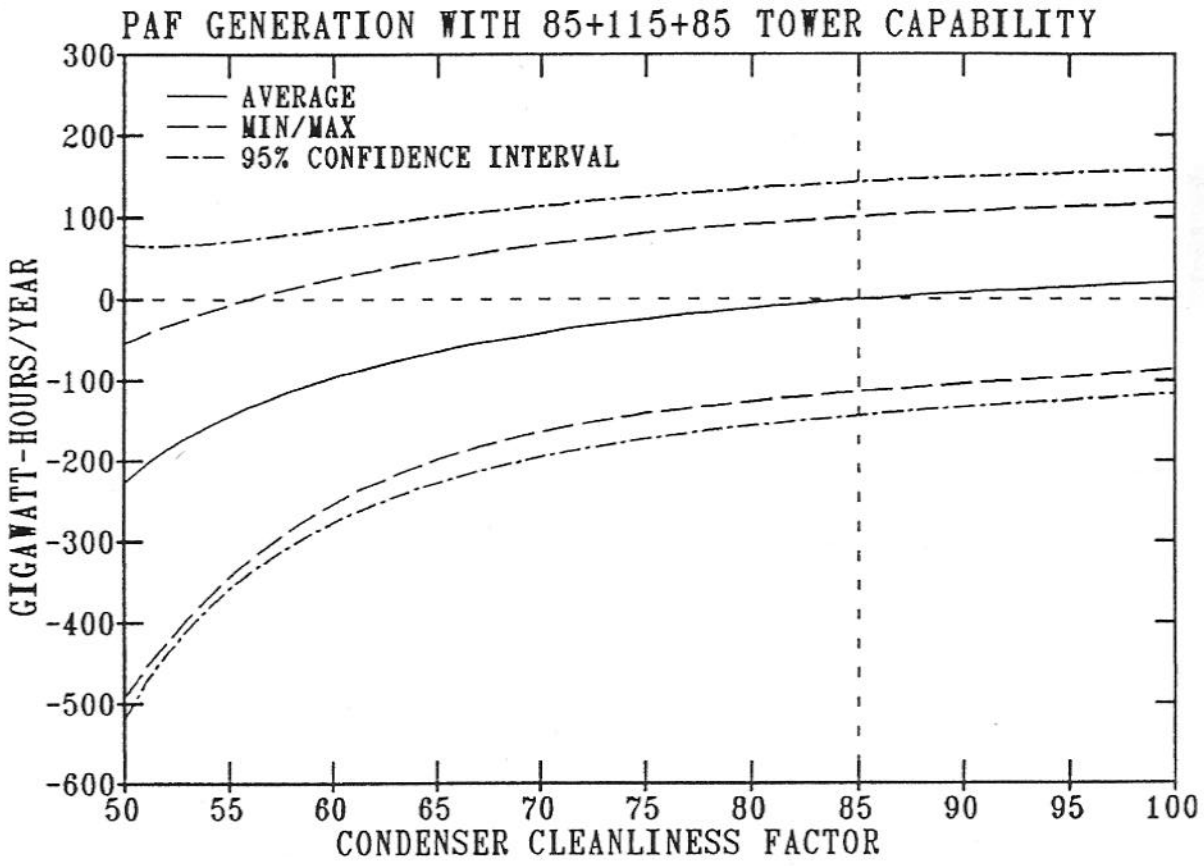


Figure 2. Impact of Condenser Cleanliness on Generation

Backpressure-Limited Operation

Figure 3 shows the number of days when one or more of the units would be forced to drop load in order to stay below 4.5 inches Hga backpressure. The conditions for each figure are the same (i.e., they represent the same simulation cases). Figure 3 shows that were the tower performance maintained at the current level, the condenser cleanliness maintained at 85 percent, and the pump flows maintained at (or brought up to) the design level, backpressure-limited operation should not be a problem at PAF. As actual experience indicates that backpressure-limited operation is a problem, one or more of these performance targets are not being maintained. [This is in no way intended to imply a lack of effort or capability on the part of the plant staff. On the contrary, it should be taken as an indication of the difficulty in maintaining these performance targets for such a complicated system which must operate under conditions such as silt-laden river water and widely variable river stage.]

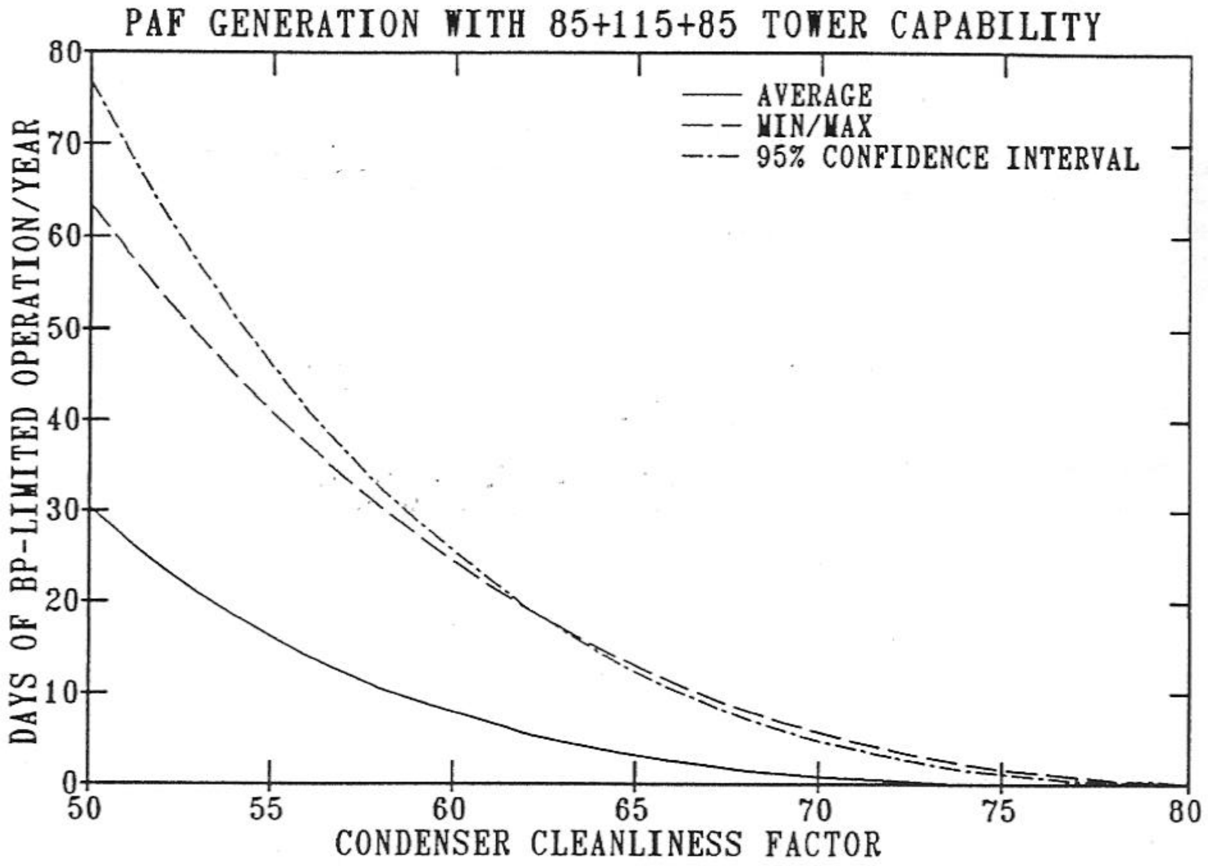


Figure 3. Days of Backpressure-Limited Operation

Impact of Cooling Tower Capability

Figure 4 shows the average annual impact of cooling tower capability on generation. The X-axis extends from a total tower capability of 200 percent (i.e., 2 towers in their original, 1969, condition) to 600 percent (i.e., the equivalent of 6 towers in their original, 1969, condition). The curves correspond to 55, 65, 75, 85, and 95 percent condenser cleanliness. The points along a vertical line at 285 percent total tower capability correspond to the solid line in Figure 2 (i.e., the average annual impact at 85+115+85=285 percent total tower capability). Figure 3 does not show the minimum, maximum, or 95 percent confidence interval. The main purpose of this figure is to illustrate how sensitive PAF is to cooling tower performance.

Figures 3 and 4 (i.e., the impact of condenser cleanliness and cooling tower performance, respectively) explain why PAF experiences significant deratings in order to meet turbo-generator and environmental constraints. Figures 3 and 4 also show the strong diminishing return with increased performance (i.e., both curves quickly level out as

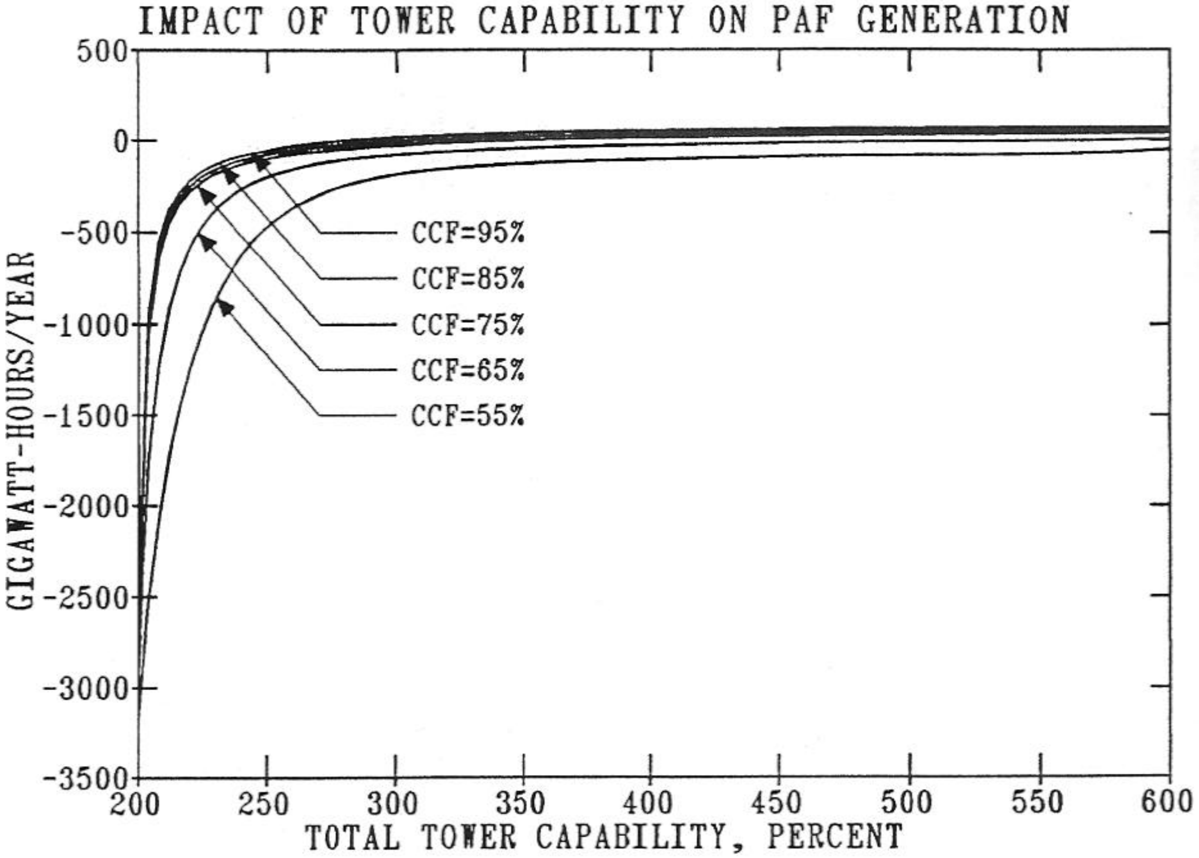


Figure 4. Impact of Cooling Tower Performance on Generation

condenser cleanliness and cooling tower capability increase). Considering operational experience in light of the environmental variability and the proximity of PAF condenser and cooling tower performance to the steeply-sloped section of the curves in Figures 3 and 4, indicates that reserve performance margin is needed for PAF to consistently achieve full capacity.

While there is a diminishing return for increasing cooling tower capability, the current level is not to the point of insignificant return, especially when considering that maintenance cannot be done while the units are operating and performance has the greatest impact as the hot season wears on. Table 4 shows the return on cooling tower upgrade in terms of gigawatt-hours generation for the average year with the 95 percent confidence interval. Table 4 is based on a constant condenser cleanliness of 85 percent. As this is not always maintained in practice, the actual impact would be higher.

Table 4 shows that the environmental variability (as indicated by the ±95 percent confidence interval) is larger than the average yearly impact. This means that the impact

Table 4. Increased Generation with Tower Capability

	Combined Capability	Gigawatt-Hours/Year
Base Case	285%	0±143
Upgrade 2 Towers	345%	33±110
Add a 4th Tower	385%	39±105
Upgrade 2 + Add 1	460%	56±90
Upgrade 2 + Add 2	575%	68±80

of cooling tower capability during extreme years is much more pronounced than during average years. Also shown in Table 4 is the decrease in the 95 percent confidence interval with increasing tower capability. This means that greater tower capability makes the plant more robust. In other words, the average generation will increase; and the expectation of full capacity during hot weather will also increase. The current NPDES discharge limits result in the significant majority of the lost generation occurring during the hot summer periods with some during periods of very low river flow. The closed-mode operation during periods when the air temperature is milder, but the river flows are very low, do not result in as significant lost generation as the cooling towers are able to provide reasonably cool water to the condensers.

CONCLUSIONS AND RECOMMENDATIONS

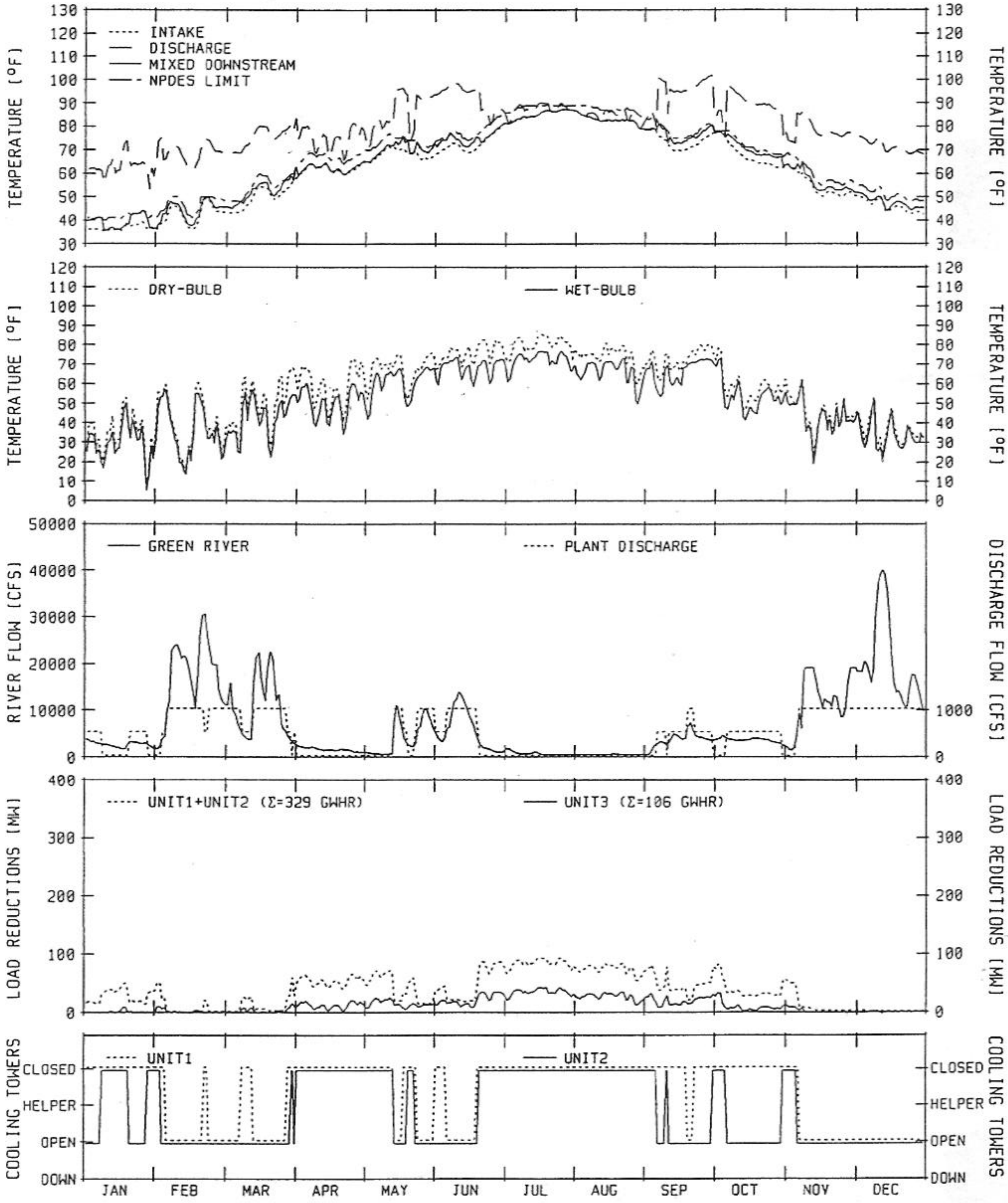
The analysis shows that PAF is susceptible to variable meteorology and hydrology, condenser cleanliness, and cooling tower capability, in that full capacity is limited by these factors. The estimated current condenser cleanliness and cooling tower performance is near the condition where susceptibility is pronounced. While there is a diminishing return on condenser cleanliness and cooling tower capability, the current performance of PAF is still within the range of significant return. As maintenance is not possible while the units are operating, and the performance is most needed during hot weather conditions, reserve performance is needed to assure full capacity during these conditions. How much reserve capacity would be cost-effective is beyond the scope of this work.

REFERENCES

Benton, D., to Brown, L., 1992, "Paradise Fossil Plant Cooling Tower 2 Performance Technical Specifications," TVA Engineering Laboratory Memorandum.

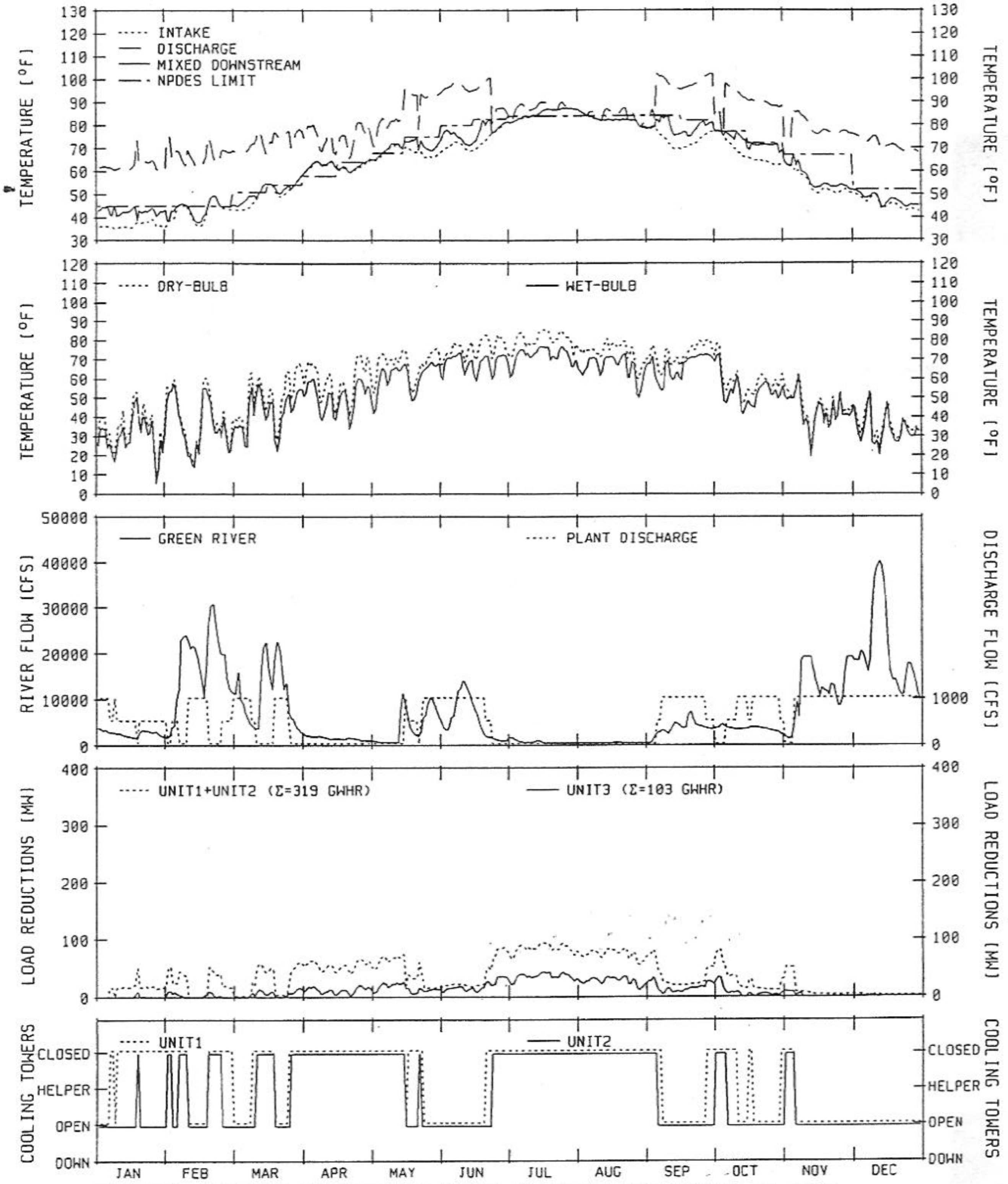
Heat Exchange Institute, 1989, Standards for Steam Surface Condensers, Heat Exchange Institute, Cleveland, Ohio.

TVA Engineering Design, 1969, "Acceptance Test Report: Cooling Towers Paradise Steam Plant Units 1-3," TVA Division of Engineering Design Report No. 40-47.



COMPUTED RESPONSE OF PARADISE FOSSIL PLANT TO THE CLIMATE OF 1986
OLD LIMITS (CONDENSER CLEANLINESS=85% COOLING TOWER CAPABILITY=100%)

ENG LAB 11/19/90



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NEW LIMITS (CONDENSER CLEANLINESS=85% COOLING TOWER CAPABILITY=100%)

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